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Impact of alternative fuel properties on fuel spray behavior and atomization

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ABSTRACT

In order to verify and solve the problem of NOx and PM emissions, it is necessary to directly observe the internal combustion chamber of a diesel engine. Many studies have been performed in recent years to verify the macroscopic and microscopic behavior of the injected fuel spray because observing it is not easy due to the difficulties of the experiment. Researchers have investigated the spray characteristics for various diesel injector nozzles over a wide range of temperatures and pressure, but there is lack of evaluation for the spray characteristics for biodiesel. At a time when rapid rise of fuel prices and depleting hydrocarbon resources of the world have forced us to look for alternative fuels biodiesel produced by transesterification of non-edible vegetable oils is promising to be an important additive/substitute to petro diesel. Biodiesel being an oxygenated and sulfur-free fuel leads to more complete combustion and lower emissions. But, the energy content or net calorific value of biodiesel is less than that of diesel fuel; also it has higher viscosity and density, than diesel fuel. A considerable improvement in these properties can be obtained by mixing diesel and biodiesel and then using the blends. Biodiesel and biodiesel/petro diesel blends, with their higher lubricity levels, are increasingly being utilized as an alternative. Present paper analyzed the correlation of injection parameters that will affect the spray characteristics of biodiesel. Observations for analyzing the effect of injection parameters on spray cone angle, break up length and fuel penetration were made. Finally the performance and emissions tests were studied. Atomization and vaporization of fuel are greatly influenced by viscosity and density of fuel and these properties are temperature dependent. Thus fuel inlet temperature plays a very important role in fuel atomization process. At higher temperature viscosity of fuel decreases which enhances the atomization of biofuels.

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1. Introduction

Energy is universally recognized as one of the most important inputs for economic growth and human development. There is a strong two-way relationship between economic development and energy consumption. Energy is the prime mover of economic growth and is vital to the sustenance of a modern economy. Future economic growth crucially depends on the long-term availability of energy from sources that are affordable, accessible and environmentally friendly.

1.1. World energy scenario

Most of the world energy needs are fulfilled through petroleum based fuels coal and natural gases. Petroleum is the largest single source energy surpassing coal, natural gas, nuclear, hydro and renewable (International Energy Agency) [1]. Fossil fuels are considered non renewable that is they are not replaced as soon as we use them. The world's total primary energy demand will swell with an annual rate of 1.7% and expected to attain a figure of 16487 Mtoe from 2002 to 2030. According to British petroleum the global energy consumption (coal, oil, gas and hydrogen, nuclear, electric) for the year 2003, 9.7 Gtoe. North America and Europe energy consumption accounts a maximum portion during the year 1990 to 2003 the consumption in the North America has grown at about 1.5% per annum, which is very near to the world average of 1.6% per annum. When talking about Asia pacific region primary energy consumption grew at approximately 3.9% per annum for the same period. The world primary consumption during 1990 was 1774.4 Mtoe, which raised to a figure of 2389.5 Mtoe in the year 2000 and further to 2908.4 Mtoe in the year 2003. The percent growth rate in primary energy consumption for the same year was calculated to be 3% and 6.8%. This reveals increased energy demands the world over. India, like many other developing countries, is a net importer of energy; more than 25% of primary energy needs are met through imports mainly in the form of crude oil and natural gas. The rising oil import bill has been the focus of serious concern due to the pressure it has placed on scarce foreign exchange resources and is largely responsible for energy supply shortages. Demand of gasoline and diesel in India is shown in Table 1.

Table 1
Demand of gasoline and diesel in India [Planning Commission of India].

Year	Gasoline demand in Mt	Diesel demand in Mt	Ratio of diesel/gasoline
2002–2003	7.62	42.15	5.53
2003–2004	8.20	44.51	5.42
2004–2005	8.81	46.97	5.33
2005–2006	9.42	49.56	5.26
2006–2007	10.07	52.33	5.20
2011–2012	12.85	66.90	5.21

1.2. Need for alternative fuels

1.2.1. Depletion of fossil fuel

At present two-third of world energy demand is met by fossil fuels like petroleum and natural gas. Limited reserves of fossil fuels and their unequal distribution have resulted in to fuel cost to raise several folds in last decade. This led to severe economical imbalance in developing countries like India, which caters to its major part of its fuel demand in oil imports Agarwal [2]. With the passage of time, this trend is likely to worsen in future causing greater scarcity and hardship. The increasing industrialization and motorization of the world has led to a steep rise in the demand for petroleum-based fuels. Energy demand is increasing due to ever-increasing number of vehicles employing internal combustion engines. Also world is presently confronted with the twin crisis of fossil fuel depletion and environmental degradation. Due to stagnating domestic crude production, the increasing trends show one and half times increase annually and if the present increasing trend continues, it would be a matter of very serious concern. Fossil fuels are limited resources; hence, search for renewable fuels is becoming more and more prominent for ensuring energy security and environmental protection. For the developing countries of the world, fuels of bio-origin can provide a feasible solution to the crisis. Dr. Rudolf Diesel invented the engine more than a century ago; he demonstrated the principle of compression ignition engine by employing peanut oil as fuel and suggested that vegetable oils would be the future fuel for diesel engines. However, petroleum discovered later, replace vegetable oils as engine fuel due to its abundant supply. Thus, it is highly desired in present context to direct the research toward renewable fuels of bio-origin, which are environment friendly, which are while being used as diesel substitute are not be harmful to human health [3].

1.2.2. Environmental concern using petroleum based fuels

The use of petroleum-derived fuel causes emissions of particulate matters sulphur and polyaromatic hydrocarbons through exhaust. Technologies for petroleum fuel extraction, transportation processing and particularly their combustion have harmful impacts on the environment. During the extraction transportation and storage of oil and gas, spills and leakage occurs, which cause water and air pollution. Refining processes also have an environmental impact however major environmental damage occur during their combustion. The petroleum fuels are mainly constituting carbon and hydrogen in addition to traces of sulphur and quality enhancer additives like oxygenates produce various gases, soot, ash and other organic compound, during combustion and when released in to atmosphere cause degradation of air quality. The increasing use of petroleum fuel will intensify the local air pollution and magnify the global warming caused by CO_2 emission Griffin [4]. Together with other green house gases like CH_4, NOx etc., more pronounced effects of global warming melting of ice caps, rise in sea level and several other aspects of climate change which include heat waves, draughts, floods, more wild fires, stronger storm etc. The devastating consequences arising out of global warming, green house Gases, ozone layer depletion and a series of other significant problems need to be managed properly.

1.2.3. Health effects of environmental pollutants

The substances that produce harmful effect on human organism and the environment called toxic substances. The following toxic substances liberated during the operation of the piston type internal combustion engines: nitrogen oxides NOx, soot, carbon monoxide CO, hydrocarbons HC, aldehydes, cancer producing substances, compounds of sulphur and lead. Besides the exhaust gases of the engines, other sources of toxicity are the crank case gases and the vaporization of the fuel into atmosphere. Maximum amount of toxic substances goes into the atmosphere due to incomplete combustion of fuel and during acceleration of the engine with the exhaust gases. In this regard, it would be appropriate to consider the related health effects of various diesel pollutants. NO from engine exhaust converted to NO_2 which can react with hydrocarbons from vehicles and other sources allowing the concentration of ozone to increase around dense traffic exposure to NO_2 is linked with increased susceptibility to respiratory infection and viral infection such as influenza, lungs irritation, edemas of lungs, increased airway resistance in asthmatics, bronchitis and pneumonia, decreased pulmonary function, increase sensitivity to allergies [6]. Ozone irritates mucous membrane of respiratory system, causes coughing clogging; damaged lungs tissue can aggravate chronic heart disease, asthma, bronchitis and emphysema [5]. SO_2 is a respiratory irritant. It can impair lung function by constructing airways and damaging lung tissues, aggregate asthma emphysema and lead to suffocation, irritation of throat. Sources of SO_2 are diesel automobiles, petroleum industries and powerhouses.

1.3. Global biofuels scenarios

Fossil fuels still represent over 80% of total energy supplies in the world today. Oil is the fossil fuel that is most in danger of running out; currently under new technological developments biofuels are also gaining importance for their use in the diesel engines. The Middle East is the dominant oil region of the world, accounting for 63% of global reserves. Global oil production scenarios based on today's production. A peak in global oil production may occur between 2015 and 2030. Countries in the Middle East and the Russian Federation hold 70% of the world's dwindling reserves of oil and gas. Renewable resources are more evenly distributed than fossil and nuclear resources, and energy flows from renewable resources are more than three orders of magnitude higher than current global energy use. Today's energy system is unsustainable because of incompetent issues as well as environmental, economic, and geopolitical concerns that have implications far into the future [6] (Fig. 1.1).

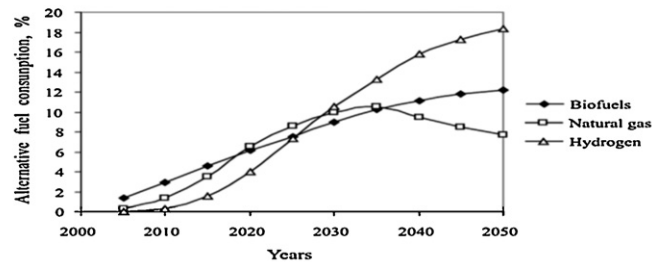


Fig. 1.1. World total automotive fuel consumption projections [29].

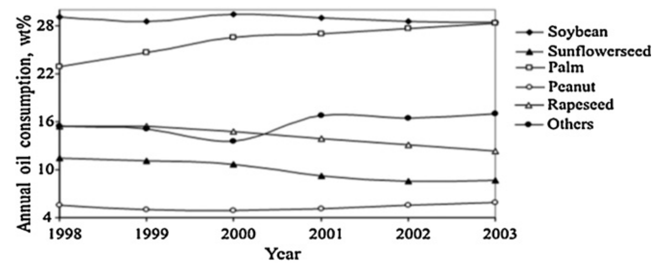


Fig. 1.2. Percentage of world oil consumption by year [29].

Vegetable oils have become more attractive recently because of their environmental benefits and the fact that they are made from renewable resources. More than 100 years ago, Rudolph Diesel tested vegetable oil as the fuel for his engine [4]. Vegetable oils have the potential to replace a fraction of the petroleum distillates and petroleum-based petrochemicals in the near future. Vegetable-oil fuels presently do not compete with petroleum-based fuels because they are more expensive. However, with recent increases in petroleum prices and uncertainties surrounding petroleum availability, there is renewed interest in using vegetable oils in diesel engines. The diesel boiling range is of particular interest because it has been shown to reduce particulate emissions significantly relative to petroleum diesel fuel [7]. World annual petroleum consumption and vegetable oil production is about 4.018 and 0.107 billion tons, respectively. Global vegetable oil production increased from 56 million tons in 1990 to 88 million tons in 2000, following a below normal increase. Fig. 1.2 shows the plots of percentages of world oil consumption by year. Fig. 1.3 shows the total global production and consumption of vegetable oil by year. Leading the gains in vegetable oil production was a recovery in world palm oil output, from 18.5 million tons in 1998 to 27.8 million in 2003.

The major exporters of vegetable oils are Malaysia, Argentina, Indonesia, the Philippines, and Brazil. The major importers of vegetable oils are China, Pakistan, Italy, and the United Kingdom. A

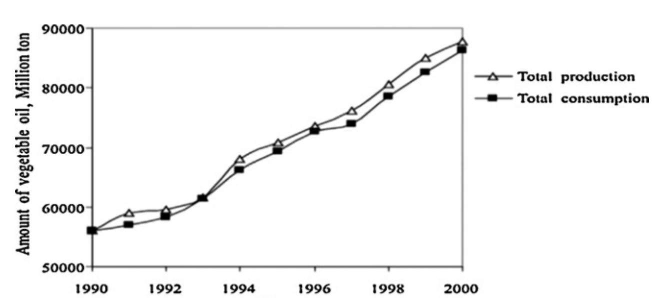


Fig. 1.3. Total global production and consumption of vegetable oil by year [9].

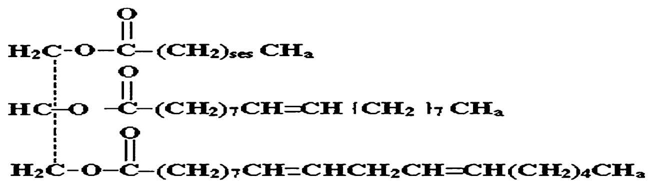


Fig. 2.1. Structure of a typical triglyceride molecule [18].

few countries such as the Netherlands, Germany, the United States, and Singapore are both major exporters as well as importers of vegetable oils [8]. Global vegetable oil consumption rose modestly from 79.5 million tons in 1998 to 96.9 million in 2003. A large portion of the gain occurred in India, where even small price shifts can cause a substantial change in consumption. Indian palm oil imports climbed to a record 2.5 million tons. Similarly, Pakistan, Iran, Egypt, and Bangladesh sharply increased their vegetable oil imports. In 1999, Pakistan reacted to falling vegetable oil prices with a series of increases that doubled the import duties on soybean oil and palm oil while eliminating duties on oilseeds. Pakistan also raised the import duty on soybean meal from 10% to 35% to stem the influx of Indian exports [9].

2. Vegetable oil resources

Vegetable oils containing up to three fatty acids linked to a glycerin molecule with ester linkages are called triglycerides. The fatty acids are characterized by their carbon chain length and numbers of double bonds. There is little difference between the gross heat content among any of the vegetable oils. Their heat contents are 88% of that of diesel D2 fuel [10]. Vegetable oils have the potential to substitute a fraction of petroleum-based engine fuels in the near future [11]. Possible acceptable processes for converting vegetable oils into reusable products such as gasoline and diesel fuel are solvent extraction, cracking, and pyrolysis. Vegetable oil fuels are not cost competitive with petroleum-based fuels. Diesel boiling range and material from plant oils is of particular interest because it has been shown to significantly reduce particulate emissions relative to petroleum diesel fuel [7].

2.1. Vegetable oil processing

Biodiesel is oxygenated, non-toxic, biodegradable, and essentially free of sulfur and compounds with ring structures (aromatics), some of which are known to be carcinogenic. Biodiesel has a lower vapor pressure and a higher flash point than diesel, making it safer to handle and store [18]. It is derived from vegetable oils or animal fats by a process known as transesterification. In the transesterification process, a triglyceride, which itself is an ester, is reacted with alcohol (methanol or ethanol) using a catalyst (KOH, NaOH). This process splits the triglyceride molecule into a mixture of methyl or ethyl esters of their free fatty acids (FFA) and the byproduct glycerol (Fig. 2.1).

Triglycerides themselves are oils composed of the glycerin ester of three fatty acids [18]. Esters are named according to the alcohol used for transesterification and the FFA in the triglyceride. For example, ester produced by reacting methanol with any vegetable oil is called a methyl ester of that oil. Ester produced by reacting ethanol with any vegetable oil is called an ethyl ester, and so on. Further, esters differ in fatty acid chain length (medium length C15–C18) as well as in the number of carbon double bonds. Methyl oleate has 18 carbon atoms and 1 double bond; whereas methyl linoleate has 18 carbon atoms and 2 double bonds. Vegetable oils are triglycerides of a variety of fatty acids. Further, the relative contribution of each fatty acid attached to the glycerin can differ depending on the feedstock or the genetics of the plant used to create the triglyceride. When these oil mixtures are transesterified to methyl esters, the various resulting compositions of methyl esters are seen to lead to slightly different combustion characteristics. This mixture of methyl esters is collectively called biodiesel [11]. The preparation of raw material includes husking, cleaning, crushing, and conditioning. The extraction processes are generally mechanical (boiling for fruits, pressing for seeds and nuts) or involve the use of solvent such as hexane. After boiling, the liquid oil is skimmed; after pressing, the oil is filtered; and after solvent extraction, the crude oil is separated and the solvent is evaporated and recovered. Residues are conditioned (e.g., dried) and are reprocessed to yield byproducts such as animal feed. Crude oil refining includes degumming, neutralization, bleaching, deodorization, and further refining [11]. Vegetable oil processing involves the extraction and processing of oils and fats from vegetable and animal resources. The oils and fats are extracted from a variety of fruits, seeds and nuts. Natural vegetable oils and animal fats are extracted or pressed to obtain crude oil or fat. These usually contain free fatty acids, phospholipids, sterols, water, odorants and other impurities. Even refined oils and fats contain small amounts of free fatty acids and water [12]. Fig. 2.2 shows transesterification reaction for vegetable oil.

Suryawanshi and Deshpande [13] reported that the transesterification involves reaction of the triglycerides of vegetable oil with methyl alcohol in the presence of catalyst (NaOH/KOH) to produce glycerol, and fatty acids ester. Specified amount of vegetable oil, methanol and sodium hydroxide were taken into round bottom flask. The mixture is stirred vigorously until ester formation begins since oil and methanol are immiscible. The mixture was heated to 70 °C and held at that temperature without stirring for one hour, and then it was allowed to cool over night without stirring. Two layers were formed. The top layer was ester. The ester has higher cetane number and low viscosity compared to vegetable oil similar methods are reported by Mittelbach [14] and Bacho Paul et al. [15].

Ghadge et al. [16] reported the transesterification reaction was carried out for Mahua oil with 0.25-v/v methanol (6:1 molar ratio) and 0.7% w/v KOH as an alkaline catalyst. The KOH amount was arrived at, based on 0.5% for catalyst plus the amount needed to neutralize the unreacted acids (i.e. 2 mg KOH/g) in the second stage product. The reaction was carried out at 60 °C for half an hour. The mixture was allowed to settle overnight before removing the glycerol layer from the bottom in a separating funnel to get the ester layer on the top, separated as biodiesel. As per reports Crude Mahua oil generally contains about 20% FFAs and the procedure for converting this Mahua oil to biodiesel is very much complicated. Also reported through experiments to optimize the pretreatment process for reducing the FFA content of Mahua oil below 1% for maximum biodiesel production. A FFA level of 19%, which was far above the 1% limit for satisfactory transesterification reaction using alkaline catalyst. Therefore, FFAs were first converted to esters in a two-step pretreatment process using an acid catalyst (H_2SO_4 1% v/v) to reduce the acid value of Mahua oil below 2 mg KOH/g. Also reported the reaction progressed rapidly during the first one hour showing over 50% reduction in acid values at low-methanol and over 80% for high-methanol ratios. After one hour, there was no significant reduction in the acid value. This might be due to the effect of water produced during the esterification of FFAs, which prevented further reaction.

Raheman and Phadatare [17] reported the kinematic viscosity of karanja oil was found to be 10.7 times more than that of diesel determined at 40 °C. After esterification, the kinematic viscosity reduced to 2.9 times than that of pure karanja oil. It further reduced with increase in diesel amount in the blend. A similar reduction in specific gravity was also observed. However, the calorific value of biodiesel was found to be 36.12 MJ/Kg, which is less than the

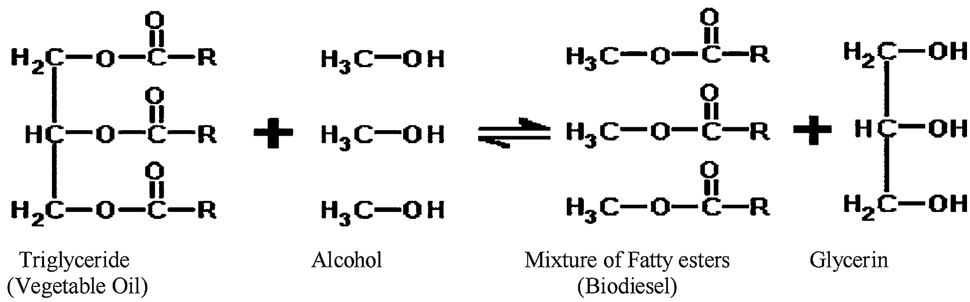


Fig. 2.2. Schematic representation of transesterification [2].

calorific value of diesel (42.21 MJ/kg) and greater than that of the karanja oil (34 MJ/kg). As the percentage of biodiesel in the blends increased, the calorific value decreased. The flash points of karanja oil and biodiesel were found to be greater than 100 °C, which is safe for storage and handling.

Monyem et al. [18] reported one drawback of biodiesel that it is more prone to oxidation than petroleum-based diesel fuel. In its advanced stages, this oxidation can cause the fuel to become acidic and form insoluble gums and sediments that can plug fuel filters. Also reported that oxidized biodiesel reduces the above mentioned problems. The oxidized biodiesel was prepared by heating 83 L of biodiesel to 60 °C in a 208 L drum and bubbling oxygen (99.6% purity) at the rate of 0.4 m^3/h through the fuel.

2.2. Use of vegetable oil in C.I. engine

Vegetable oil can be directly used with diesel fuel and may be used for running an engine. The blending of vegetable oil with diesel fuel were experimented successfully by various researchers. In 1980 caterpillar, a Brazilian company used pre combustion chamber engines with a mixture of 10% vegetable oil to maintain total power without any modification in engine. A blend of 20% oil and 80% diesel was used successfully. It has been proved that the use of 100% vegetable oil was also possible with some minor modification in the fuel system. The high fuel viscosity with the use of vegetable oils caused major problems in CI engines.

Forson et al. [19] used Jatropha oil in proportion of 97.4:2.6%; 80:20% and 50:50% blends of diesel and Jatropha oil by volume in CI engine. It was found that carbon dioxide emissions were similar for all fuel blends. The test further showed increase in break thermal efficiency and brake power and reduction of specific fuel consumption for Jatropha oil and its blends with diesel fuel. But the most significant conclusion from the study is that the 97.4% and 2.6% diesel and Jatropha fuel blend produce maximum value of the brake power and brake thermal efficiency as well as minimum value of the specific fuel consumption. D97.4: B2.6 fuel blend yielded the highest cetane number and even better engine performance than the diesel fuels. It was suggested that Jatropha oil could be used as an ignition accelerator additive for diesel fuel.

Puhan Sukumar et al. [20] found that straight vegetable oil can be used in diesel engines. Their high viscosity, low volatilities and cold flow properties have led to the investigation of various derivatives. In this study Mahua oil was transesterified with methanol using sodium hydroxide as catalyst to obtain mahua oil methyl ester and was tested in a single cylinder four stroke diesel engine to evaluate the performance and emissions.

Pramanik [21] studies the effect of temperature on the viscosity of biodiesel and Jatropha oil. Significant improvement in engine performance observed as compare to vegetable oil alone but specific fuel consumption and exhaust gas temperature were reduced due to increase in viscosity of vegetable oil. From engine test results it has been established that 40–50% of Jatropha oil can be substituted for diesel giving acceptable thermal efficiency without any engine modification and preheating of the fuel blends.

Nwafor [22] studied the performance of rapeseed oil blends in a diesel engine. The experimental result showed that a mixing ratio of 30% and 70% diesel rapeseed ratio was practically optimal in ensuring relatively high thermal efficiency of engine. Knocking problem encountered at light loads was attributed to the longer ignition delays due to the low cylinder temperature. Operation with vegetable fuel oil offered a net reduction in HC emissions compared with base line results. The 50:50 blends competed favorably with diesel oil and offer a reasonable substitute for diesel fuels.

2.3. Emission behavior of C.I. engine

The combustion process in CI engine occurs only at the interface between the injected fuel system and air compressed in the cylinder. Thus, oxidation of fuel is not always complete. The incomplete combustion of the fuel produces CO, HC and oxygen containing compounds such as aldehyde. In addition, the temperature in the cylinder during combustion also promotes the production of NOx from nitrogen and oxygen in air; the equivalence ratio plays an important role in the control of engine emissions. It is defined as the actual fuel-air ratio divided by the stoichiometric fuel-air ratio; at very low value this NOx can be significantly reduced. If the fuel air mixture becomes very lean then it becomes increasingly more difficult to ignite [23,20]. The most familiar emission from a CI engine is the characteristic smoke produced when engine operates under load. White smoke can be produced when the fuel injection is initiated too late during the cycle or when compression ratio is too low. Blue smoke is typically caused due to excessive lubrication oil entering in the combustion chamber because of poor piston ring, sealing and valve guide wear. Gray-blue smoke is typically generated when the engine is operating at or near full load and too much fuel is injected or when air intake is partially obstructed. Heavy smoke from an engine usually indicates a loss in thermal efficiency, power output and fuel economy. Gray-black smoke results from poor maintenance of air filter and fuel injectors or from improper adjustment of the fuel injection pump. The chemical composition of fuel, cetane number and volatility affect gray-black smoke production in diesel engines [24]. The combustion process in CI engine occurs only at the interface between the injected fuel system and air compressed in the cylinder. Thus, oxidation of fuel is not always complete. The incomplete combustion of the fuel produces CO, HC and Oxygen containing compounds such as aldehyde. In addition, the temperature in the cylinder during combustion also promotes the production of NOx from nitrogen and oxygen in air; the equivalence ratio plays an important role in the control of engine emissions. It is defined as the actual fuel-air ratio divided by the stoichiometric fuel-air ratio. At very low value of equivalence ratio, the NOx can be significantly reduced. If the fuel air mixture becomes very lean then it becomes increasingly more difficult to ignite [25,26].

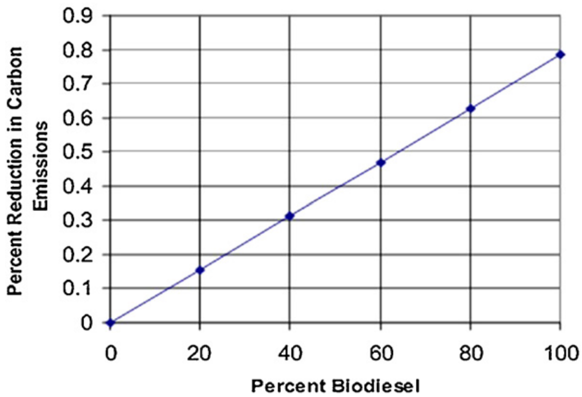


Fig. 2.3. Percentage reduction in air emission for diesel, B20, and B100 [55].

2.3.1. CO_2 emissions

CO_2 is not considered as a pollutant from combustion point of view as complete combustion would lead to high CO_2 emissions. On the other hand, CO_2 is an important pollutant from environmental point of view. The fuel-contained carbon and hydrogen by combustion with oxygen are converted into CO_2 and water vapor as products. The carbon content of some fuels by weight is 84–87% (diesel), 75% (CNG), 82% (propane), 37.5% (methanol), 52.2% (ethanol) and 0% (hydrogen). The development of new technologies are mainly targeted for reducing regulated emissions such as CO, HC, particulate emissions resulting in high CO_2 emissions. In general, conventional fuels are mostly carbon-based fuels, which would generally lead to carbon-based emissions such as CO_2, CO, HC, and particulate emissions [27].

2.4. The greenhouse effect and global warming

Carbon dioxide is transparent to light but rather opaque to heat rays. Therefore, CO_2 in the atmosphere retards the radiation of heat from the earth back into space. The "greenhouse effect" climate warming is expected to follow from the increasing emission of carbon dioxide in the atmosphere. Carbon is accumulating in the atmosphere in the form of carbon dioxide (CO_2) as the result of fossil fuel combustion, land use change, and tropical deforestation. Global surface temperatures have been measured and have increased by approximately 0.6 °C in the past century. Observations of the retreat of glaciers, lengthening of the growing season, rising minimum temperatures and other phenomena have been interpreted by many scientists as manifestations of an enhanced greenhouse effect (Fig. 2.3).

There is great potential to decrease atmospheric carbon concentrations through biospheric sequestration. Biosphere carbon sequestration can contribute too many ancillary environmental benefits, which will redound to the favorable public perception of the Greening Earth Society (GES), such as development of urban forests, greenbelts, reforestation projects, land reclamation, promotion of biomass energy, and greenways. Demirbas [11] reported that it is important to recognize that there are many carbon sequestration approaches other than in the terrestrial biosphere. For example, research is underway to determine if carbon can be captured at the point of generation and deposited in deep geological strata. Carbon can also be sequestered in the ocean and other bodies of water. At the tailpipe, biodiesel (most of which is renewable) emits 4.7% more CO_2 than petroleum diesel. The non renewable portion comes from methanol. Biodiesel generates 573.96 g/bhp-h compared to 548.02 g/bhp-h for petroleum diesel. The higher CO2 levels result from combustion that is more complete and the concomitant reductions in other carbon-containing tailpipe emissions. The overall life cycle emissions of CO_2 from B100 are 78.45% lower than those of petroleum diesel. The reduction is a direct result of carbon recycling in soybean plants. B20 reduces net CO_2 emissions by 15.66%.

2.5. Biodiesel as a potential diesel engine fuel

Biodiesel is an oxygenated fuel containing 10–15% oxygen by weight. In addition, it can be called a sulfur-free fuel. These facts lead biodiesel to more complete combustion and reduce most of the exhaust emissions from diesel engine. But, comparing the fuel properties of biodiesel and diesel fuel, it has higher viscosity, density, pour point, flash point and cetane number than diesel fuel [16]. In addition, the energy content or net calorific value of biodiesel is about 12% less than that of diesel fuel on a mass basis. Using biodiesel can help reduce the world's dependence on fossil fuels and it also has significant environmental benefits. On the other hand, most of the researchers have reported that 100% biodiesel emits lower tail pipe exhaust emissions compared to the diesel fuel; nearly 50% less in PM emission, nearly 50% less in CO emission and about 68% less in HC emission. Furthermore, since biodiesel can be called a sulfur-free fuel, it has 99% less SOx emission than the diesel fuel. However, most of the biodiesels produce 10–15% higher oxides of nitrogen (NO) when fueling with 100% biodiesel. Depending on the abundant availability of feedstock in local region, the different feed stocks are focused for the biodiesel production [16].

2.6. Economics of biodiesel

The major obstacle to produce biodiesel is higher cost than petroleum diesel. It has been observed that the selling price of Jatropha and Other plant oils might be 2.5 times more than diesel price [28]. However; the actual cost will depend also on economies of scale in manufacturing and the political decision to promote biodiesel in the country. The cost factor is considered taking in view the increased rural employment opportunities, indigenous energy sufficiency and savings of foreign exchange. Generation of employment in plantation and seed collection is estimated to be 40 persons per day per hectare. There would also be employment generation in storage; oil extraction etc. The estimated cost of biodiesel is about 17–19 Rs/L. The glycerin and cake would be valuable products, which further reduces the cost of biodiesel. Oil cake used as a raw material for production of biogas would be a leverage to start many type of industries. Reduction of tax on biodiesel by government is one of the effective ways to bring down the cost in the beginning. Austria, Italy and Spain have zero duty rates. Initially a reduced duty rate structure will be required to promote these fuels in the country.

2.7. Biodiesel and fatty acid composition

Knothe et al. [29] pointed out that biodiesel from vegetable oils with high amounts of saturated fatty acids (low iodine numbers) will have a higher cetane number while the low-temperature properties are poor. However, biodiesel from vegetable oils with high amounts of unsaturated fatty acids (high iodine numbers) will have low cetane number while the low-temperature properties are better. Gerhard Knothe and Steidley [30] investigated the kinematic viscosity of numerous fatty acid compounds, which are mainly contained in biodiesel. They found that the kinematic viscosity of fatty compounds is significantly influenced by compound structure and influencing factors are chain length, position, number and nature of double bonds, as well as nature of oxygenated moieties (Figs. 2.4 and 2.5).

Graboski and McCormick [31] expressed in their paper that the chemical composition of fat and oil esters is dependent upon the

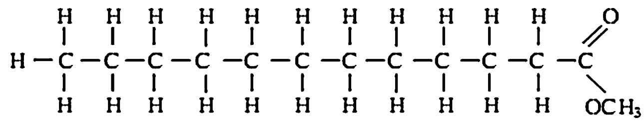


Fig. 2.4. Example of saturated fatty acid (lauric acid) [31].

Table 2.1
Chemical structure of common fatty acids [1].

Fatty acid	Systematic name	Structure	Formula
Lauric	Dodecanoic	12:0	$C_{12}H_{24}O_2$
Myristic	Tetradecanoic	14:0	$C_{14}H_{28}O_2$
Palmitic	Hexadecanoic	16:0	$C_{16}H_{32}O_2$
Stearic	Octadecanoic	18:0	$C_{18}H_{36}O_2$
Arachidic	Eicosanoic	20:0	$C_{20}H_{40}O_2$
Behenic	Docosanoic	22:0	$C_{22}H_{44}O_2$
Lignoceric	Tetracosanoic	24:0	$C_{24}H_{48}O_2$
Oleic	Cis-9-Octadedeconoic	18:1	$C_{18}H_{34}O_2$
Linoleic	Cis-9,cis-12 Octadedeconoic	18:2	$C_{18}H_{32}O_2$
Linolenic	Cis-9,cis-12,cis15 Octadedeconoic	18:3	$C_{18}H_{30}O_2$
Erucic	Cis-13, Decosanoic	22:1	$C_{22}H_{42}O_2$

length and degree of unsaturation of the fatty alkyl chains. In addition, they stated that the cetane number of fatty acid increases with the chain length, decreases with number of double bonds and carbonyl groups move toward the center of the chain.

Yamane et al. [32] carried out a study in order to investigate the effect of fatty acid methyl ester content on the peroxide value and acid value of biodiesel. Based on their investigation they reported that polyunsaturated fatty acid methyl ester, such as linoleic acid methyl (C18:3) can be oxidized easier than linoleic acid methyl (C18:2) and oleic acid methyl (18:1). By reviewing these literatures on fatty acid composition on biodiesel, most of the researches were emphasis on the fuel properties of biodiesel such as viscosity, pour point, cetane number and oxidation stability. It is noted that the saturated FAMEs type biodiesels have much higher cetane numbers than the unsaturated FAMEs type biodiesels.

2.8. Properties affecting atomization

In the references cited on the theory of atomization and droplet, burning it is evident that there are some key parameters, important for atomization and burning characteristics. These properties are viscosity, surface tension, density, latent heat of vaporization, thermal conductivity, specific heat capacity, boiling point and heat of combustion [33].

2.8.1. Biodiesel properties

Since biodiesel is produced from vegetable oils and animal fats, the properties of finished biodiesel depend mainly on the feedstock. On the other hand, the main components of vegetable oils and animal fats are fatty acids and therefore fatty acid compositions influence the properties of biodiesel. These properties are both physical and chemical properties, including the fuel properties (cetane number, viscosity, density, bulk modulus and pour point), combustion characteristics [fuel injection timing, ignition delay and ignition timing] and exhaust emissions (HC, CO, NOx and smoke). Table 2.1 shows chemical structure of fatty acid and the effects of fatty acid composition on biodiesels were studied by researchers Knothe et al. [29,30], Graboski et al. [31], and Yamane et al. [32].

2.8.1.1. Density. The density is usually expressed as a specific gravity. The density is directly proportional to the bulk modulus. The density, speed of sound and bulk modulus makes the greatest effect on the injection timing of the diesel engine. Higher density and bulk modulus of fuel require earlier injection timing. The early injection timing produces higher cylinder temperature or more NOx emission [34]. The density, speed of sound and bulk modulus increase as the chain length increases and is higher for more unsaturated ester [4]. In addition, the bulk modulus of saturated fatty acid methyl ester is lower than that of unsaturated fatty acid methyl ester (FAMEs). By contrasting among saturated FAMEs, slightly higher densities can be found in larger carbon number saturated FAMEs. It can be seen from the literature of vegetable oil methyl ester fuels and FAME fuels that, saturated FAMEs type biodiesels have lower density than the unsaturated FAMEs type biodiesels [31].

2.8.1.2. Kinematic viscosity. Viscosity is a measure of fluid resistance to flow. The greater the viscosity, the less readily the liquid flows. In diesel combustion, high viscosity leads to poorer atomization of the fuel spray, less accurate operation of fuel injector and more deposit formation in fuel injector and combustion chamber [35]. Also it is known that when the viscosity of the fuel increases, the cone angle of fuel spray decreases, and the diameter of fuel droplets and their penetration increase. Thus, the liquid of fuel spray can touch the combustion chamber wall and the piston surface, causing heavy carbon deposits on the walls, piston ring sticking and breaking, and diluting the lubricating oil [36]. Moreover, high viscosity can cause early fuel injection due to high line pressure, which moves the combustion of the fuel closer to top dead center, increasing maximum pressure and temperature in the combustion chamber [29,30]. In FAMEs, when chain length increases, the viscosity increases, and when the degree of unsaturation increases, the viscosity decreases [30]. Comparing kinematic viscosity of FAME fuels in this study, ML100 and MOL50 have lower kinematic viscosity and their values are close enough to that of the diesel fuel.

2.8.1.3. Distillation temperature. The distillation temperature of a fuel is to determine the fuel volatility. Lower distillation temperature means higher or good fuel volatility and it makes better fuel air mixture in the combustion process. The boiling points of FAMEs increase with the carbon number and decrease when the degree of unsaturation increases [30].

2.8.1.4. Pour point. The pour point is a measure of cold flow property of a fuel. At pour point temperature, the fuel cannot be flown. The pour point temperatures become higher as the chain length increases in saturated FAMEs and become lower for more unsaturated FAMEs [38]. Therefore, the vegetable oil methyl ester fuels which do not have sufficient cold flow property are difficult to use in cold region. It is necessary to improve the cold flow properties of these fuels by using cold flow improver or some additives to lower the pour point.

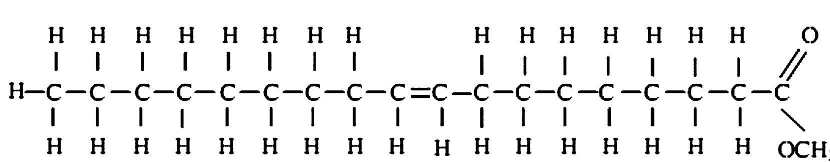


Fig. 2.5. Example of unsaturated fatty acid (Oleic acid) [31].

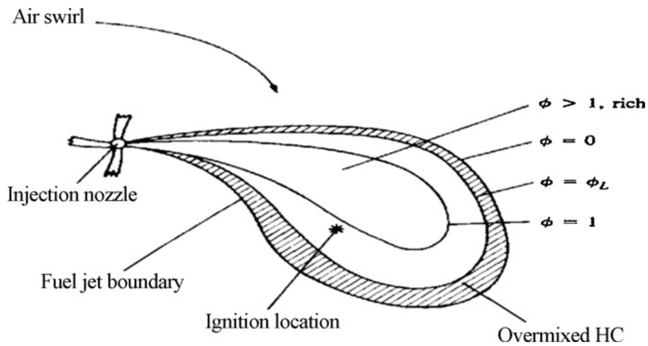


Fig. 2.6. Schematic of diesel engine fuel spray showing equivalence ratio (Φ) contours at time of ignition [39].

2.9. *Fatty acid composition and combustion characteristics of biodiesel*

In combustion process, the fuel is injected into combustion chamber under high pressure, and then it atomizes into small droplets and begins to evaporate as it moves away from the fuel injector (Table 2.2).

As shown in Fig. 2.6, the fuel air ratio at any point in the combustion chamber may range from zero, at a point with no fuel, to infinity, inside a fuel droplet that has not yet vaporized. In general, the fuel-air ratio is high near the fuel injector tip and low away from it, but because of the complexity of the mixing process, the fuel-air ratio does not change uniformly within the combustion chamber. Combustion can only occur within a certain range of the fuel-air ratio; if the ratio is too low, there is not enough fuel to support combustion, and if the ratio is too high, there is not enough air to take combustion process [39].

As the injected fuel vaporizes into the hot air, it starts to oxidize. As more fuel vaporizes and mixes with air, the number of the oxidation reactions increase until the end of the ignition delay period, when ignition occurs at many locations independently and combustion propagates very rapidly in regions which have fuel-air ratio in the combustible range. As shown in, Fig. 2.7, this initial combustion after ignition is called the premixed combustion phase; it consumes only about 5–10% of the fuel used by the engine at typical full-load operation. At the end of the premixed combustion phase, most of the fuel is yet to be injected or is still in a region that is too rich to burn. But injection continues and fuel continues to vaporize and mix with air, aided by heat release and turbulence generated by the premixed combustion. This quickly generates more gas with the required fuel-air ratio and combustion continues. This is the diffusion-controlled phase of combustion and, ideally consumes all of the remaining fuel. Most of the biodiesels have suitable cetane numbers for occurrence of diesel combustion process. Furthermore, biodiesel is an oxygenated fuel which containing 10–15% oxygen by

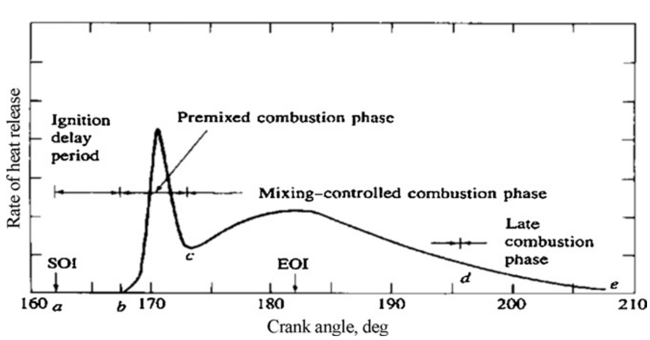


Fig. 2.7. Diesel engine heat release rate diagram with combustion phases [39].

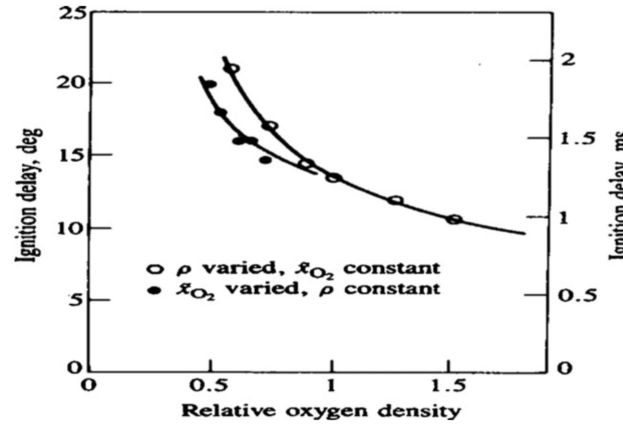


Fig. 2.8. Effect of oxygen density in gas on ignition delay [39].

weight and that provides biodiesel to take combustion that is more complete. In order to understand the combustion characteristics of biodiesel, FAME fuels and vegetable oil methyl ester fuels, fuel injection timing, fuel injection interval, combustion start timing, ignition delay time and heat release rate of these will be discussed from the literature as follows.

2.10. *Fuel injection timing*

The fuel injection timing is mainly influenced by the physical properties of the fuel especially density, bulk modulus and kinematic viscosity of the fuel. Higher density, bulk modulus and kinematic viscosity of fuel has less damping action and leads to faster needle lift and injection timing. The earlier injection timing causes faster combustion and relating the increase of maximum pressure and temperature in the combustion chamber, and higher exhausts emissions.

2.10.1. *Fuel injection interval*

The fuel injection interval is the duration of fuel injection from fuel injector into the combustion chamber of diesel engine. The fuel injection interval varies with the heating value or net calorific value of the fuel. Fuel having lower net calorific value is needed in greater amount to liberate the same amount of heat in the combustion process. Therefore, fuel having lower net calorific value takes longer fuel injection time compared to one having higher net calorific value. Combustion start timing is greatly important for the combustion process of a diesel engine. Improper combustion start timing causes incomplete combustion process and other negative effects like increase in HC, CO and smoke emissions. Faster injection timing and the higher cetane number affect the combustion start timing (Fig. 2.8).

2.10.2. *Ignition delay time*

Ignition delay time shows the ignition ability of a diesel fuel. It is the period between the start of injection and the start of combustion. As shown in Fig. 2.9, the ignition delay time is mainly influenced by the cetane number of the fuel. It is known that larger cetane number fuel has shorter ignition delay time. It is a fact that the long chain, saturated, unbranched hydrocarbons have suitable cetane number and good ignition ability as diesel fuel; while unsaturated, and branched hydrocarbons have lower cetane number and poor ignition ability [40]. But lower amount of premixed combustion is expected to be a result of shorter ignition delay, which provides less time for the preparation of premixed fuel. Lower distillation temperature of fuel means higher volatility or vaporization of fuel. Higher volatility allows much amount of fuel to vaporize during ignition delay period thus increasing the amount of

Table 2.2
Chemical composition of vegetable oils [1].

Vegetable oil	Fatty acid composition (wt%)									
	14.0	16.0	18.0	20.0	22.0	24.0	18.1	22.1	18.2	18.3
Corn	0	12	2	Tr	0	0	25	0	6	Tr
Cottonseed	0	28	1	0	0	0	13	0	58	0
Crambe	0	2	1	2	1	1	19	59	9	7
Linseed	0	5	2	0	0	0	20	0	18	55
Peanut	0	11	2	1	2	1	48	0	32	1
Rapeseed	0	3	1	0	0	0	64	0	22	8
Safflower	0	9	2	0	0	0	12	0	78	0
H.O. Safflower	Tr	5	2	Tr	0	0	79	0	13	0
Seasame	0	13	4	0	0	0	53	0	30	0
Soya bean	0	12	3	0	0	0	23	0	55	6
Sunflower	0	6	3	0	0	0	17	0	74	0
Rice-bran	0.4–0.6	11.7–16.5	1.7–2.5	0.4–0.6	–	0.4–0.9	39.2–43.7	–	26.4–35.1	–
Sal	–	4.5–8.6	34.2–44.8	6.3–12.2	–	–	34.2–44.8	–	2.7	–
Mahua	–	16.0–28.2	20.0–25.1	0.0–0.3	–	–	41.0–51.0	–	8.9–13.7	–
Neem	0.2–0.26	13.6–16.2	14.4–24.1	0.8–3.4	–	–	49.1–61.9	–	2.3–15.8	–
Karanja	–	3.7–7.9	2.4–8.9	–	–	1.1–3.5	44.5–71.3	–	10.8–18.3	–

Tr: Traces.

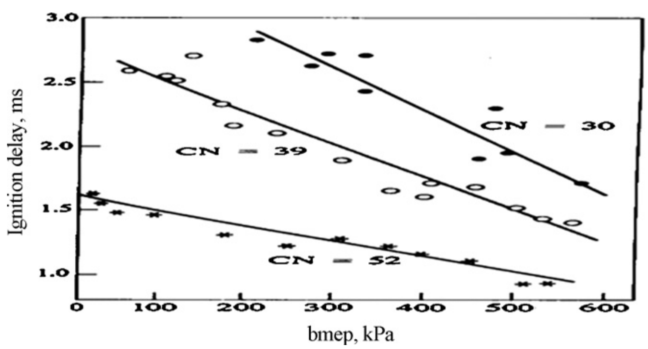


Fig. 2.9. Measured ignition delays for diesel engine for fuel cetane nos., 30, 39 and 52 [49].

combustible mixture in the combustion chamber and premixed portion of the combustion. Longer ignition delay time makes more combustible mixture and premixed combustion and if the same amount of fuel burns, the higher net calorific value fuel may emit more heat quantity in the combustion process.

2.11. *Effect of fuel spray pattern on atomization*

Liquid sprays consist of different sizes of droplets dispersed in a gaseous medium. They are dispersed in atmosphere and are indispensable for daily activities. They include natural phenomena such as rain, fog and waterfall mists, or are generated using mechanical devices like nozzles for different applications such as in medicine (pulmonary drug delivery), cosmetics, various industries (painting and fuel injection), agriculture (pesticide sprays), fire suppression systems (sprinklers), household applications (printers) etc. Fuel spray characteristics are considered to play the most important role in combustors from the standpoint of thermodynamic performance, level of pollutant emissions and acoustic instabilities. In liquid sprays, droplet size frequency and spatial distributions control fundamental flame characteristics such as length, stability, radiant heat transfer, smoke and the formation of nitrous oxides [26] (Fig. 2.10).

2.11.1. *Droplet formation*

Atomization is the jet breakup regime which occurs in diesel engines. The fluid's surface tension, viscosity and density along with the jet diameter, relative velocity between the jet and its surroundings, and turbulence are very important parameters in atomization. The Sauter Mean Diameter (SMD) is commonly used as a measure of the quality of atomization in diesel engines. There have been several models developed using various techniques for SMD and droplet breakup. One of the common ones is the TAB method developed by O'Rourke and Amsden [41]. This model treats the spray system as a "damped, forced harmonic oscillator" and is used in the numerical analysis of spray combustion systems. It however requires the determination of constants from experimental data obtained with specialized equipment and parameter setup. Reitz and Diwakar [42] gave a very simple correlation for SMD as follows:

$$SMD = B\frac{\sigma_f}{\rho_f V_0^2}$$

where P_f = density of the fuel; σ_f = surface tension of the fuel; V_o = velocity of the fuel jet and B = a constant.

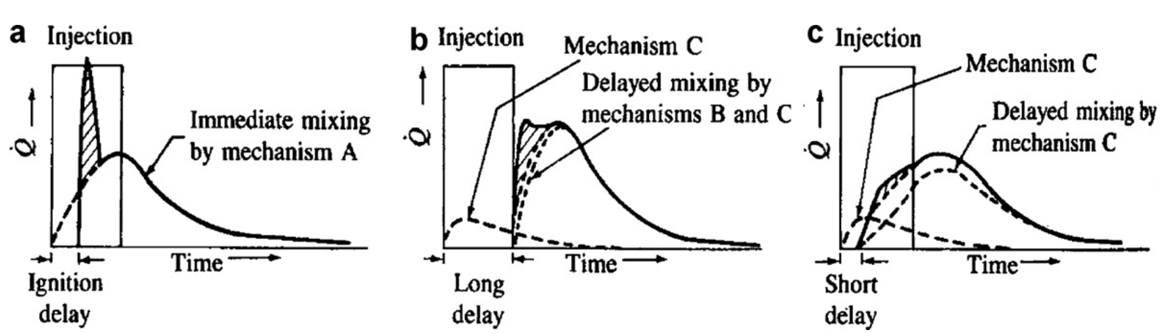


Fig. 2.10. Schematic injection rate and burning rate in combustion system (a) multi hole nozzle (b) M-type engine fuel injected on wall (c) IDI swirl chamber engine [39].

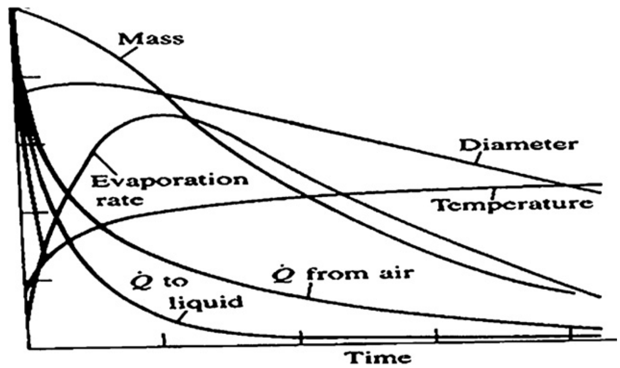


Fig. 2.11. Schematic of variation of mass, evaporation rate, diameter, temperature, heat transfer rate to liquid drop core as function of time during evaporation process [39].

2.11.2. Droplet evaporation and combustion

Evaporation is the first process encountered in the combustion of a droplet (Fig. 2.11).

The stages through which evaporation occurs [43] are:

- An initially cold droplet is heated by its surrounding hot atmosphere mainly through thermal conduction.
- The temperature of the droplet increases up to a point where it remains constant. At this point additional heat is consumed as latent heat and the droplet starts to vaporize.
- As vaporization continues, mass transfer between the atmosphere and the surroundings starts by way of diffusion. This is due to the concentration gradient of the vapor.
- A final state is reached where the rate of mass transfer comes in equilibrium with the rate of heat transfer and a steady state is achieved.

2.12. Problems associated with vegetable oil used in C.I. engine

A number of problems are encountered while using vegetable oil directly as a diesel engine fuel. High viscosity of vegetable oil is the major constraint in using straight vegetable oil as diesel engine fuel. The ultimate effect is reducing the life of engine. The high viscosity increases the problem of fuel injection and atomization and contributes to incomplete combustion making cold starting difficult, nozzle clogging, excessive engine deposits, ring sticking, contamination of lubricating oil etc. Poor volatility makes vegetable oil difficult to vaporize and ignite, this results in thermal cracking resulting in heavy smoke emission and carbon deposits in the combustion chamber. The problems of high viscosity can be overcome to a great extent by various techniques, such as heating, dilution, emulsification and esterification.

Giannelos et al. [7] reported viscosity of tobacco oil fuel is important to its flow through pipeline, injector nozzles, orifices and for atomization of a fuel in cylinder and suggested to prohibit its direct use as an alternative fuel in diesel engine, but it could be used in blends with diesel or after catalytic transesterification.

Mittelbach [14] reported, higher content of phosphorous in unrefined rapeseed oil methyl ester can lead to higher particulate emissions which may influence the operation of catalytic converter. Higher content of water in biodiesel might reduce the storage ability or lead to separation of water when blending with diesel. He also suggested free glycerol can be easily removed by washing steps. Higher content of glycerol may cause problems during storage or in the fuel injection system due to separation of glycerol, or can lead to injector fouling or the formation of higher aldehyde emissions. A higher content of triglycerides may cause formation of deposits at the injection nozzle, at the piston and at valves.

Bhatt et al. [25] reported problems of carbon deposition on injector tip, piston head, valve faces and piston ring grooves was more with pure karanja and Mahua oil along with pumping and atomization problems for karanja and rice bran oil.

Huzayyin et al. [28] reported, short-term test indicated good potential for most vegetable oil fuels. However, long term endurance tests show that there are some problems, such as injector chocking, ring sticking, gum formation and lubricating oil thickening. These problems are related with high viscosity and non-volatility of neat vegetable oil. Poor atomization patterns associated with high fuel viscosity results in increasing the combustion chamber deposits and the introduction of unburned fuel in the lubricating oil.

Rao and Gopalkrishnan [44] reported considerable drop in thermal efficiency for neem, palm, rice bran and karanja oil and found lowest efficiency for rice bran oil due to its maximum density and viscosity. Also reported higher delay period than that of diesel for all the vegetable oils, and neem has highest ignition delay. Only a marginal variation in peak pressure from that of diesel oils except for neem oil which is due to its higher combustion delay. Reported drop in combustion duration for all vegetable oils by about 1–2 °CA whereas for neem oil 6–8 °CA. Also reported that pure oil of peanut and soybean produced heavy smoke and deposition, they also cause starting difficulties. Also carried out experiment with neem, palm, rice bran and karanja oil and reported considerable increase in smoke, poor combustion characteristics of oil due to high viscosity and poor volatility, rice bran oil, having the maximum density and viscosity among the oil tested, gave the lowest efficiency. Repugnant odour was noticed while operating the engine with palm oil.

Karaosmanoglu et al. [36] reported, during the test for sunflower oil, the engine experienced no significant difference in drop or increase of power, fuel consumption and balancing force. Also reported further 5 min start/heat up and shut down with diesel fuel, were quite helpful.

Antony and Samaga [45] reported that comparing the performance of diesel and groundnut oil, the performance of diesel is superior at all loads. The higher exhaust temperature of vegetable oil is an indication of their delayed combustion, partly because of their slower combustion rates and partly due to prolonged injection on account of their lesser calorific value and hence lesser thermal efficiency. Also reported negligible heat release immediately after injection before the uncontrolled stage of combustion. This corresponds to the delay period, which is higher than diesel by 1–2 °CA, the difference being less at higher loads. Peak rate of heat release and hence the peak rate of pressure rise was lower for the vegetable oil. Peak burned gas temperatures were slightly higher, which correspondingly increase the peak equilibrium NO and CO concentrations for the vegetable oil.

Antony and Samaga [45] reported the higher exhaust temperatures of vegetable oils (groundnut oil) is an indication of their delayed combustion, partly because of their slower combustion rates and partly due to prolonged injection on account of their lesser calorific value.

Verma et al. [46] reported Crude Jatropha carcus gave higher brake specific energy consumption at all loads; crude Jatropha oil gave very low magnitude of brake thermal efficiency in comparison with diesel. Also reported increase in exhaust gas temperature for all the operating conditions of vegetable oil compared to diesel fuel operation.

Jajoo and Keoti [47] reported nozzle deposits formed with both soyabean and rapeseed oils are harder and required moderate scraping for removal. He also reported economic study of vegetable oils reveal that vegetable oils are not an economic substitute for diesel at present.

Gopalkrishnan et al. [48] reported high carbon residue causes heavy smoke emission and carbon deposition on the injection

nozzle tips and in the combustion chamber. These problems are less pronounced in indirect injection engines.

2.13. Engine performance with esters

Suryawanshi and Deshpande [13] reported the brake thermal efficiency was similar as compared to diesel at part and full load and it was better at 400 Kpa bmep as compared to diesel for all blends of Jatropha methyl esters with diesel. The brake thermal efficiency with biodiesel was about 31.67% for JME (100%) where as it was about 31.59%with diesel at 600 Kpa bmep. Similar trends were observed for 20%, 40%, 60%, 80% biodiesel. The brake specific energy consumption is slightly higher as compared to diesel at all loads; this may be due to lower calorific value of biodiesel. Further reported variation of cylinder peak pressure for various blends of biodiesel. The peak pressure rate of cylinder pressure rise was similar for biodiesel and its blends as compared to diesel. There was difference of 0.2 Mpa between the peak pressure with JME100 and diesel at full load. This difference decreases for lower blends of biodiesel. Exhaust gas temperature was observed for all blends of JME with diesel. JME100 has shown 404 °C and diesel 400 °C at full load. Also reported that brake specific energy consumption is more reliable parameter than brake specific energy consumption to compare the two fuels, as calorific value and density of blends follow slightly different trends. Further found b.s.f.c was higher for all blends of JME and it is due to less calorific value of biodiesel.

Forson et al. [19] conducted an experimental study of Jatropha Curcas oil diesel blends on a single cylinder air cooled Lister model DI four stroke diesel engine and they claimed that 2.6% Jatropha curcas oil with 97.4% diesel were the optimum blends to give higher thermal efficiency and brake power with reduction in specific fuel consumption, these results are contradictory to those presented in [62] used Jatropha oil with inferior properties and diesel with superior properties.

Puhan Sukumar et al. [20] reported the specific fuel consumption was higher (20%) than that of diesel and thermal efficiency was lower (13%) than that of diesel.

Bhatt et al. [25] reported the result of short term engine performance with karanja and Mahua oil were quite encouraging, particularly the power output, specific fuel and energy consumption and brake thermal efficiency for 20% and 40% blends were quite closer to the neat diesel fuel performance.

Huzayyin et al. [28] reported the performance of engine with engine speed at two-third engine load using blends of 20%, 40%, and 60% jojoba oil with gas oil as compared to 100% diesel. During test, reported the engine power and bmep slightly decreases and b.s.f.c slightly increases with the increase of jojoba oil percentage in the fuel blend, they remain constant at full engine load. This may be due to decrease in calorific value of the blend fuel with increase of jojoba oil percentage in the blend.

Kalam and Masjuki [35] reported the IRGANOR NPA (product name) was used as the corrosion inhibitor, which was claimed to improve the corrosion control in lube oil. When it was added to fuels, metal protection limits the formulation of ions, which catalyze oxidation processes to gum formation. The palm oil methyl ester blend (POD) (50 ppm anticorrosion/corrosion inhibitor +15% POD + 85% diesel) increased 10–15% higher brake power. Also reported decrease in wear metals (Fe, Cu, Al and Pb) and additives (Zn, Ca) depletion as compared to diesel. Viscosity changes were normal for both the POD blends.

Jajoo and Keoti [47] reported the blends of soyabean oil show still lower efficiencies. It has been also observed that increasing percentage of soyabean oil reduces the brake thermal efficiency further. As calorific values of these oils were less than diesel fuel and their viscosity was more than diesel oil and volatility less than diesel oil, such performance was quite expected. In both cases smoke levels were higher with blends than that with diesel. This can attributed to higher fraction of particulate bound hydrocarbons. Higher viscosity and low volatility are also responsible for higher smoke levels. It was observed that exhaust gas temperatures are little higher at higher loads for blends of these oils with diesel.

Senthil Kumar et al. [49] from their experimental study reported the use of Jatropha oil methyl ester in single cylinder four stroke small sized direct injection water-cooled Kirloskar base diesel engine. Reported reduced brake thermal efficiency and increased SFC, higher exhaust gas temperature, smoke density, HC, and CO but lower NOx emission and longer delay at all loads in comparison to diesel operation. During Jatropha oil methyl ester (JOME) operation, higher density and lower heating value fuel was the reason for increased SFC and lower thermal efficiency. These observations were in accord with the observations of other investigators. Reduction in NOx concentrations and increase in the concentrations of CO, HC and smoke density indicate inefficient combustion with JOME which indicates that engine operating and design parameters be changed for efficient combustion.

Pramanik [21] reported that there was a decrease in brake thermal efficiency and increase in specific fuel consumption when Jatropha oil-diesel blends were used as fuel. The reason he claimed for increased SFC was combined effects of the relative density, viscosity and heating value of the blends and for decreased thermal efficiency was poor combustion characteristics of Jatropha oil due to higher viscosity and poor volatility. It is claimed in his paper that blends containing 30:70 and 40:60 J/D have SFC very close to that of diesel. However the actual values reported by him are 7% and 15% higher respectively. Also claimed that higher exhaust temperature with blends was indicative of lower thermal efficiencies of the engine which is obvious, however, the higher exhaust gas temperature also point to the late burning of fuel and hence inefficient combustion process.

Reddy et al. [50] carried out experimental study on the effect of variation in injection system parameters viz: injection timing, injector opening pressure, injection rate and swirl level on the performance and emission of Jatropha oil and reported the optimum injection parameters for higher thermal efficiency and lower emissions as: static injection timing 33.5° BTDC, injector opening pressure 220 bar, injection rate corresponding to the 9 mm plunger diameter. Also demonstrated the effect of injection system parameter on the heat release diagram and on various stages of combustion, employed swirl enhancement to determine its effect on performance and emission and found that thermal efficiency has not been improved but HC and smoke levels were decreased significantly with swirl. However it increases NOx level considerably. A more detailed study to analyze quantitatively the effect of swirl on the performance improvement is required.

Usta [51] reported among the blends, D82.5/TSOME17.5 provided the maximum increase in the torque, power and thermal efficiency. The maximum increase in power occurred at 2000 rpm as 8.74 kW. This value is 3.13% higher than the power 27.84 kW obtained with the diesel fuel. Furthermore, the peak thermal efficiency was observed at 2500 rpm as 29.8%. This is approximately 2.02% higher than thermal efficiency of the diesel fuel.

Vijaya Raju et al. [52] reported when the injection pressure increased, the SFC of non-esterified and esterified Jatropha oil was decreased. However the SFC of esterified Jatropha oil as compared to diesel oil was higher. The higher density of esterified fuel has led to more discharge of fuel for the same displacement of the plunger in the fuel injection pump. Further reported at part load engine operation has deteriorated with the increase in injection pressure from 210 to 320 bar. However, full load operation of the engine at injection pressure 320 bar has resulted in better performance of engine. High injection pressure produces smaller droplets with lesser momentum and hence shallow penetration. Similarly low

injection pressure results in larger droplet size, high peak pressure throughout the range of operation of the engine.

Charles Peterson et al. [53] reported during case study on rapeseed ethyl ester, the dynamometer test at 2500 rpm showed 1.8% less power, and 8.9% less fuel economy, and 31.8% less opacity when operated on biodiesel in comparison to diesel fuel. Vehicle performance was extremely good and no problem was encountered.

Cheng et al. [54] reported the freezing and gelling of many biodiesel formulations are limiting their applications. Soybean-based methyl esters, the most common in the US, will become cloudy and gel at temperatures near 0 °C and −5 °C when used in cold ambient temperatures. At the cloud point, long-chain hydrocarbons (or saturated fatty acid ester in biodiesel) begin to form small wax crystals, and when numbers of wax crystals with diameters exceeding 0.5 mm are large they plug fuel filter systems. Further reported the Primary solutions to minimize bulk flow and fuel filter block problems include: (a) Utilization of fuel tank, fuel line and fuel filter heaters. (b) Utilization of additives (pour point depressants, anti-gel additives, or cold flow improvers) that impact crystal morphology. Additives are developed to distort the crystal shape and to some extent alter their size, or directly inhibit their growth habit, thereby reducing pour point temperatures. (c) Blending with a fuel like kerosene, which causes freezing point depression. Blending sufficient amounts of kerosene-type components can improve the cold flow properties of diesel fuel blends. However, kerosene's use must be limited because increasing amounts decrease calorific value and fuel lubricity. Also reported adding 0.75% OS-110050 additive with 70 and 80% vol. LSD no.2 produced a cloud point of −15 °C and pour point of 29 °C a significant reduction in these properties over neat biodiesel.

2.14. Biodiesel emissions

Suryawanshi and Deshpande [13] reported in case of biodiesel smoke emissions are less as compared to diesel. The maximum reduction in smoke emission was observed by 35% in case of neat biodiesel operation as compared to diesel. There is significant reduction in smoke emission for all blends at part and full load; this is due to soot free and complete combustion because of oxygenated fuel of biodiesel blends. He reported significant reduction in HC emission for all biodiesel blends as compared to diesel at part and full load. HC emission was further reduced with an increase in blending of JME. The unburned hydrocarbon drastically reduced by 53% for neat biodiesel operation. The similar trends were observed for various blends of biodiesel with diesel. Further reported O_2 content in exhaust was more with biodiesel and reported biodiesel leads to slightly higher NOx level as compared to diesel. The average increase of NOx was by 5% for blends as compared to diesel. This may be attributed to complete combustion of oxygenated fuel.

Puhan Sukumar et al. [20] reported exhaust pollutant emission were reduced compared to diesel. Carbon monoxide, hydrocarbon, smoke number, oxides of nitrogen were reduced 30%, 35%, 11%, 4%, respectively.

Reddy et al. [50] reported esterified Jatropha oil has become simple structure by transesterification resulting in less smoke. Also reported and found no scope to bring down the smoke level by raising the injection pressure beyond 210 bar. Also reported high temperatures for esterified Jatropha oil, high CO_2 concentration, less CO and O_2.

Usta et al. [51] performed test on turbocharged indirect injection diesel engine and reported the addition of tobacco seed oil methyl ester decreased CO emission due to the fact that TSOME contains about 11.4% oxygen by weight, and this oxygen helps to oxidize the combustion products in the cylinder. There was a significant SO_2 reduction with blends due to lower sulphur content of the biodiesel. NOx emissions slightly increased due to higher combustion temperature and the presence of fuel oxygen with blend at full load. However, the increasing amounts of NOx emission slow down with decreasing loads. Although the oxygen concentration was higher at partial loads, the combustion temperature and time decrease, leading to low NOx. Also, it is known that the external oxygen supplied with air is less effective than the fuel-borne oxygen in the production. As a result of all of the findings mentioned above, it can be concluded that tobacco seed oil methyl ester can be partially (up to 25–30%) substituted for diesel fuel no.2 at most operating conditions in terms of performance parameters and emissions without any engine modification and preheating of the blends.

Charles Peterson et al. [53] reported about rapeseed methyl ester emissions tests showed a reduction in HC (55.6%), CO (50.6%) and NO (11.8%) and an increase in CO (1.1%) and PM (10.3%). The results for PM are not significantly different from diesel.

Raheman and Phadatare [17] reported the experiment was carried out for esterified karanja oil (B100) and its blends. The minimum and maximum CO produced was 0.004%, 0.016% resulting in a reduction of 94% and 73% for B20 and B100 as compared to diesel. The minimum and maximum density produced for B20–B100 was 1% and 3% with minimum and maximum reduction of 80% and 20% respectively as compared to diesel. The amount of NOx produced for B20 and B100 was varied between 4 and 12 ppm as compared to 12 and 13 ppm for diesel, on an average 26% reduction in NOx was obtained for biodiesel and its blends as compared to diesel. He reported the reduction in emissions (CO, smoke density and NOx) could be due to complete combustion of fuel as compared to diesel. Exhaust temperature for above blends varied between 260 °C and 360 °C as compared to 262 °C and 335 °C for diesel indicating not much variation in exhaust temperature, this could be due to same quantity of fuel consumed per hour for diesel and biodiesel blends.

Kalligeros et al. [55] reported the fuels tested were typical Greek marine diesel and mixtures containing 10%, 20%, 50%, by volume sunflower oil and olive oil biodiesel, its addition into the marine fuel improves all the emissions and specifically particulate matter, which comprises a serious problem for the diesel and marine diesel engines, especially in, polluted areas such as ports and beaches. PM emissions generally enhance or decrease in relation to the sulfur concentration. Sulfur into the fuel, results in sulfates that were absorbed on soot particles and increase the PM emitted from diesel. The aromatics have high carbon–hydrogen ratios and thus fuels with lower aromatics will lead to a smaller amount of CO_2 and larger amount of H_2O being formed compared to high aromatic fuels since H_2O has a lower tendency to dissociate at high temperatures (compared to CO_2). The reason for the decrease in NOx was that the cetane numbers of the biodiesel were higher than that for the marine diesel fuel, and this is usually associated with lower NOx emissions. Increasing cetane number reduces the size of premixed combustion by reducing the ignition delay. This results in lower NOx formation rates since the combustion pressure rises more slowly, giving more time for cooling through heat transfer and dilution and leading to lower localized gas temperatures.

Moneyem et al. [18] reported the neat oxidized biodiesel at the standard injection timing had about 13% higher NOx emissions than the diesel fuel while the unoxidized biodiesel had about 14% higher. The oxidized biodiesel reduced the CO emissions over 28% compared with diesel fuel and 15% compared to the unoxidized biodiesel at the full-load engine condition. Also reported all neat biodiesel and biodiesel blends produced lower emissions of unburned hydrocarbon with a maximum reduction of 51% for the neat oxidized biodiesel compared with diesel fuel. The oxidized biodiesel produced 16% lower HC emissions than the unoxidized biodiesel. Further reported the Bosch smoke number was significantly reduced when the diesel engine was fueled with neat biodiesel and its blends with diesel fuel. The highest reduction was

found for the oxidized biodiesel. It reduced the smoke number from 1.4 to 0.5 compared with diesel fuel.

Kidoguchi et al. [56] reported the experimental results that fuel is gasified, thermally cracked and dehydrogenated during the ignition delay period, which produces mainly unsaturated hydrocarbons such as C_2H_2, C_2H_4, and C_3H_6 in the diffusion combustion stage, the LHCs consist mainly of CH_4. When the injection pressure is increased, a large amount of LHCs are formed during the ignition delay period, resulting a high initial heat release rate and short combustion duration. At the late diffusing burning stage, high pressure injection condition produces a smaller amount of gaseous hydrocarbons. When injection pressure is increased, NOx concentration increases during combustion. However higher distillation temperature fuel increases combustion duration which reduces NOx.

2.15. Formation of NOx

Control of pollutant emissions from fuel burning engines is of major environmental concern worldwide, especially for engineers who design engine components with the aim of minimizing the emission of nitrogen oxides (NOx). NOx are very undesirable emissions, play a major role in the formation of acid rain, greenhouse effect and the global warming issue, and hence accelerates the process of icecap melting in north and south poles

2.15.1. Thermal NOx

Basically, NOx, as the name implies, are generated from reaction between nitrogen and oxygen under high temperature and pressure conditions during the combustion process in an engine cylinder. Normally it takes place at the pre-combustion, combustion and post-flame regions where sufficient concentrations of oxygen and nitrogen are present.

$$N_2 + O \leftrightarrow NO + N \quad (1)$$

$$N + O_2 \leftrightarrow NO + O \quad (2)$$

$$N + OH \leftrightarrow NO + H \quad (3)$$

$$H + N_2 \leftrightarrow N_2H \quad (4)$$

The formation of NOx depends enormously on the temperature, as the rate of dissociation of nitrogen is directly proportional to the temperature increase. Therefore, the higher the combustion reaction temperature, the more NOx will be produced [37,38].

$$N2H + O \leftrightarrow NO + NH \quad (5)$$

It is formed by the stabilization of atmospheric nitrogen in oxidizing atmospheres at a high flame temperature exceeding 1300 °C. When the combustion is under fuel-lean conditions (with less air) and there is a rise in temperature, this will lead to an increase of NOx emissions due to increased oxygen radicals forming in the combustion process. High activation energies are required for the dissociation of oxygen molecules and the disengagement of the triple bond of nitrogen. This phenomenon causes the formation of thermal NOx to be largely dependent on the temperature, degree of air to fuel mixing, concentration of oxygen and nitrogen in the flame and duration of reaction occurred [39].

2.15.2. Fuel NOx

It is formed by the reaction of fuel-bound nitrogen compounds with oxygen at temperature exceeding 850 °C. The formation of fuel NOx is mainly dependent on the availability of oxygen and the combustion method. Under low oxygen conditions, hydrogen cyanide (HCN) reacts with oxygen atoms to form oxycyanogen and amine intermediates and NO is formed as the oxidization product [39].

$$NH_2 + NO \rightarrow N_2 + H_2O \quad (6)$$

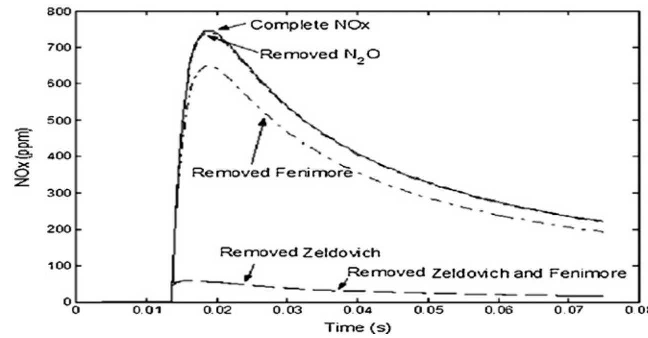


Fig. 2.12. Contribution of various NOx mechanisms to NOx emissions of Methylbutanoate Note that the curves for removed Zeldovich, and removed Zeldovich and Fenimore overlap [39].

$$CH + NO \rightarrow HCN + O \quad (7)$$

On the other hand, under excess oxygen conditions, the formation of N_2 is more favorable as the result of additional hydrogenated amine species and NO.

2.15.3. Prompt NOx

It is formed by the stabilization of atmospheric nitrogen in reducing atmosphere by particles of hydrocarbon under fuel-rich conditions.

Prompt NOx is of great significance under the condition of very fuel-rich flames and nonessential to be compared with the influence of thermal and fuel NOx Heywood (Fig. 2.12).

2.16. Emission reduction with biodiesel

Replacing petroleum diesel with biodiesel reduces life cycle air emissions for all the pollutants tracked. The largest reduction (34.5%) in air emissions that occur when B100 or B20 is used as a substitute for petroleum diesel is for CO. The effectiveness of B20 in reducing life cycle emissions of CO drops proportionately with the blend level. Biodiesel could, therefore, effectively reduce CO emissions in CO non-attainment areas. B100 exhibits life cycle TPM emissions that are 32.41% lower than those of the petroleum diesel life cycle. As with CO, the effectiveness of biodiesel in reducing TPM drops proportionately with blend level. This is a direct result of reductions in PM10 at the tailpipe, which are 68% lower for B100 versus petroleum diesel. PM10 emitted from mobile sources is a major EPA target because of its role in respiratory disease. Urban areas represent the greatest risk in terms of numbers of people exposed and levels of PM10. Using biodiesel in transportation may be an option for controlling life cycle emissions of TPM and tailpipe emissions of PM10.

2.16.1. Smoke and soot reductions

Smoke (particulate material) and soot (unburned fuel and carbon residues) are of increasing concern to air quality problems that are causing a wide range of adverse health effects for citizens, especially in terms of respiratory impairment and related illnesses. The lack of heavy petroleum oil residues in the vegetable oil esters that are normally found in diesel fuel means that an engine operating with biodiesel will have less smoke i.e. 27.7% reduction for B100 and 5.55 reduction for B20 respectively, and less soot produced from unburned fuel. Further, since the Biodiesel contains oxygen, there is an increased efficiency of combustion even for the petroleum fraction of the blend. The improved combustion efficiency lowers particulate material and unburned fuel emissions especially in older engines with direct fuel injection systems. Agarwal [2] oxygen present in biodiesel is shown to be the driving mechanism for soot reduction in engine operating on various blends of biodiesel.

The higher the oxygen contents of the Biodiesel blend, the greater the reduction in soot emissions.

2.17. Fuel modification: effect of fuel heating on engine performance

Kalam and Masjuki [35] reported that preheated crude palm oil has reduced exhaust emissions such as CO, HC and PM as compared to diesel and crude palm oil and emulsified fuels. This is due to preheating of CPO which reduces its viscosity to the level of diesel fuel that improves the fuel spray characteristics and produces complete combustion.

Verma et al. [46] reported that heating was one of the effective methods to utilize vegetable oils as fuels. Besides that, preheating of vegetable oil to lower its viscosity to that of diesel eased the problem of the injection processes. Heating is also essential to ensure smooth flow of fuel in the fuel system [17].

Senthil Kumar et al. [49] reported that the peak pressure and rate of pressure rise are found as high with animal fat at higher fuel inlet temperatures, improvement in premixed combustion phase with preheated animal fat is also reported.

Agarwal and Agarwal [57] reported high viscosity of vegetable oil (30–200cSt @ 40 °C) as compared to mineral diesel (4cSt @ 40 °C) lead to unsuitable pumping and fuel spray characteristics. Larger size fuel droplets are injected from injector nozzle instead of a spray of fine droplets, leading to inadequate air–fuel mixing. Poor atomization, lower volatility and in sufficient mixing of fuel with air contribute to incomplete combustion. This results in an increase in higher particulate emissions, combustion chamber deposits, gum formations and unburned fuel in the lubricating oil. It was found that heating the Jatropha oil between 90 °C and 100 °C is adequate to bring down the viscosity in close range to diesel. Viscosity of Jatropha blends (up to 30%) was also found close to diesel. Optimum fuel injection pressure was evaluated, which was found to be 200 bar for diesel and preheated Jatropha oil. Pre heating the Jatropha oil reduces viscosity. Therefore, pre heating Jatropha oil does not lead to change in optimum fuel injection pressure.

Agarwal and Rajamanoharan [58] reported, single cylinder diesel engine ran successfully during tests on Karanja oil and its blends even without preheating and require modification in engine hardware. However, while using preheated fuel, engine efficiency improved slightly. Performance and emission characteristics of Karanja oil and its blends were found to be comparable to that of mineral diesel. Thermal efficiency of the engine with preheated oil blends is nearly 30% and for lower blends (unheated) such as K10, K20 and K50, it was 24–27%. The brake specific fuel consumption and brake specific energy consumption of the engine with preheated lower blends showed an improved trend.

Agarwal and Rajamanoharan [58] reported the friction power was noted to increase, with a decrease in fuel viscosity, while mechanical efficiency plots showed reversed trends. The heated oil fuel showed an increase in peak cylinder pressure, compared to the diagrams obtained for diesel fuel and unheated fuel operations. The peak pressure diagram of the heated fuel exhibited combustion characteristics similar to pure diesel fuel operation. This clearly indicates that under favorable conditions, the performance of vegetable oil fuel can exceed that of diesel fuel operation. There was significant increase in HC emissions when running on diesel fuel. The overall test results showed that fuel heating was beneficial at low speed operation and under part-load test conditions. It has been shown that vegetable oil fuel has good potential as a substitute for diesel fuel. The fuel consumption of heated and unheated oil operations at high loads was similar and higher than diesel fuel operation. The results indicate increase in exhaust temperature with heated oil over the other fuels. The

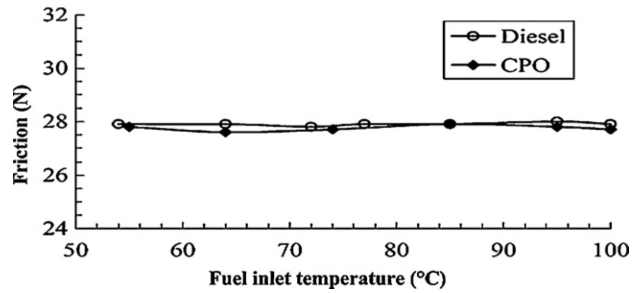


Fig. 2.13. The effects of fuel inlet temperature on friction [62].

heated fuel showed a comparative reduction in delay period over the unheated fuel. The unheated oil and diesel fuel operations showed an increase in CO production as the load was increased. One major obstacle in using vegetable oils (of which CPO is one) is their high viscosity, which causes clogging of fuel lines, filters and injectors [59], therefore, vegetable oils cannot be used directly in diesel engines at room temperatures. In order to reduce the viscosity of the vegetable oils, three methods were found to be effective transesterification, mixing with lighter oil and heating. To examine the effects of fuel inlet temperature on the injection system and to find a suitable temperature to heat CPO to lower its viscosity for use in diesel engines; to compare the performance, combustion characteristics and emission of CPO with those of diesel.

Pugazhvadivu and Jayachandran [60] reported that the preheated waste frying oil at 135 °C could be used as a diesel fuel substitute for short term engine operation.

Nazar et al. [61]. Have reported that preheated Karanja oil and Neem oil have significant improvement in engine performance and reduction in HC and CO emissions when compared to crude oils.

Till today preheating of vegetable oil is done through external source i.e. with electrical heater. Preheating of vegetable oil through electrical heater shows improvement in many aspect but engine efficiency reduce due to extra source of heating which consumes energy from engine itself.

2.18. Effects of heating on injection system

Bari et al. [62] reported on effect of fuel heating on system component. Fig. 2.13 shows the results of the modified friction test that involved motoring while injecting the fuel outside the combustion chamber. The total friction values for both CPO and diesel were almost identical, and were quite stable throughout the whole temperature range, up to 100 °C. For CPO, the friction was around 27.8 N, while for diesel, it was about 27.9 N. Therefore, a fuel heating temperature of up to 100 °C was assumed to have no adverse effect on the injection pump. Otherwise, thermal expansion of the plunger barrel assembly could have caused significant changes in friction between the moving parts. However, it was important to bring out the point that the pumping power of the fuel injection pump was low compared with the overall motoring power of the engine. Therefore, in accuracy of judgments could exist. Nevertheless, it can be seen that the friction for CPO was insignificantly lower than that of diesel.

The viscosity of CPO at room temperature is too high to allow smooth flow in Fuel lines. To lower its viscosity, CPO needs to be heated. The modified friction test Performed to investigate the influence of heating showed that heating of fuel up to 100 °C had no adverse effects on the fuel injection system. However, heating of CPO offered no advantages in terms of performance, but was necessary for the fuel to flow smoothly in the fuel system. The required

smooth flow of CPO was achieved at temperatures of 60 °C and above, at which all solid phase CPO had dissolved.

3. Concluding remarks

Researchers from various countries carried out extensive experimental investigations using vegetable oil as fuel in compression ignition engine applications. The critical view of above literature reveals that most of the investigators have found higher BSFC of the engine for the same power output while using vegetable oil, biodiesel, diesel fuel blends compared to diesel. However esters of karanja oil in particular and that of other vegetable oil in general show a better performance as compared to any plane vegetable used as fuel. It has been established through the review of literature that diesel fuel BSFC is always lower than any other stated fuels. These results show that thermal efficiency and power output were slightly lower when Karanja oil methyl ester was used in place of diesel in conventional diesel engines. The reasons for lower thermal efficiency, lower power output and higher specific fuel consumption are, Karanja oil methyl ester has slightly higher viscosity slightly higher density lower volatility and lower calorific value resulting in larger droplet sizes, higher fuel discharge by the injection pump for the same displacement, poor mixture preparation and poor air entertainment leading to insufficient, incomplete combustion. The results of crude Karanja oil diesel blends as fuels gave lower thermal efficiency and reduced power output in comparison to diesel operations. However use of Karanja oil with superior properties blended with diesel gave higher thermal efficiency and increased power output at all load conditions in comparison to diesel. There were significant changes in exhaust gas emissions for different operating load and speed conditions. The reduction in hydrocarbons and carbon monoxide and increase in NOx emission has also been found by majority of investigators while using biodiesel as substitute fuel to diesel. Hence, Karanja oil in esterified form or blended form can be considered as suitable potential diesel substitute for diesel engine application. However, the cetane number of the yellow grease biodiesel was so high that it suppressed the premixed portion of the combustion and lowered the brake specific oxides of nitrogen emission relative to biodiesel. It was concluded from the above literature cited that use of biodiesel reduces pollutants like CO, CO_2, and HC except NOx emissions. It has also been reported that performance improved with lower percentage substitution of diesel fuel but it caused the problem of injector chocking and sticking, gum deposition and seizing of flow under adverse atmospheric condition, which led to affect the smoothness of engine operation under long-term performance. The review of reported literature highlights following points.

- World is presently confronted with the crisis of fossil fuel depletion and environmental degradation. India, a fast growing economy facing the challenge of meeting a rapidly increasing demand for energy, ranks sixth in the world in terms of energy demand.
- This involves revenue to face the environmental problem and to meet energy demand.
- There is considerable scope of increase in the production of oilseed in India by extending irrigation facilities, utilizing wasteland for oil seed cropping and adopting suitable agricultural technologies. Using efficient expellers can also increase vegetable oil production.
- A comparison of physical and fuel properties of vegetable oils with those of diesel fuel indicate that vegetable oils are quite similar in nature to diesel fuel and can be used as diesel engine fuel. However, vegetable oils have exceptionally high viscosity and slightly higher density.
- The approaches for using vegetable oils as supplementary substitute diesel engine fuel include the use of vegetable oil ester (biodiesel), vegetable oil blends with diesel and heated vegetable oils before injection. These are primarily aimed to reduce the viscosity of vegetable oils.
- The droplet size is affected by several fuel properties including surface tension, specific gravity, and viscosity.
- The presence of oxygen in the biodiesel fuel leads to more complete combustion in the diesel engine.
- Problems encountered with the use of straight vegetable oil, vegetable oil blends and heated oils in the present day unmodified compression ignition engines include injector chocking, increased carbon deposits in combustion chamber and piston ring grooves, increased lubricating oil contamination and marginally higher wear rate. These problems are however not unsurmountable. Pure esters of vegetable oil show a better response, although lubricating oil contamination is there.
- B-100 biodiesel has about 50% higher viscosity than petroleum diesel, which means that when the injectors try to atomize the thicker fuel, larger droplets will form in the fuel spray.
- Fuel injection temperature should be high as compared to intake air temperature if so better mixing of charge takes place inside the chamber and reduces NOx and PM emissions.
- The thermal efficiency and power output were slightly lower and fuel consumption was slightly higher when Jatropha oil methyl ester used in place of diesel in conventional diesel engines.
- The reasons for lower thermal efficiency, lower power output and higher BSFC are, related to fuel properties like lower calorific value and higher delay period, high delay period is due to higher viscosity of biodiesel. Lower Calorific value and higher delay period results in higher fuel discharge by the injection pump for same power output.
- The results of crude vegetable oil and diesel blends as fuels gave lower thermal efficiency and reduced power output in comparison to diesel operations. However uses of vegetable oil with superior properties, blended with diesel with inferior properties gave higher thermal efficiency and increased power output and all load conditions in comparison to diesel.
- There were significant changes in exhaust gas emissions for different operating load and speed conditions. Hence Jatropha oil in esterified form or blended form can be considered as suitable potential diesel substitute for diesel engine application.
- While using blends up to 30% concentration of vegetable oil and diesel reported comparable engine performance without any modification in engine as given by neat diesel fuel.
- All diesel-fueling infrastructures can be used for biodiesel without modifications. Biodiesel is safe to handle because it is biodegradable and non-toxic. Biodiesel is safe to transport as biodiesel has high flash point compared to diesel fuel.
- It is found from the literature that biodiesel is denser and less compressible than diesel fuel and that the chain length and saturation increase the density speed of sound and isentropic bulk modulus. It has been reported by researchers that biodiesel has lower exhaust emissions compared with petroleum-based diesel fuel; 20% less carbon monoxide (CO) emission, 30% less hydrocarbon (HC) emission, 50% less soot emission, and 40% less particulate matter emission. Also, since biodiesel is a sulfur-free fuel, it has 99% less sulfur oxide (SOx) emission than diesel fuel and SOx is known to be one cause of acid rain. However, biodiesel has about 10–15% higher NOx emissions.
- As suggested by the researchers higher NOx is related to: (a) higher cycle temperature due to higher delay period. (b) Higher oxygen content of the fuel. As for higher delay period, the reason attributed is sluggish atomization due to higher density and viscosity. However esters of vegetable oil and that of their blends with diesel are reported to have higher cetane number.

- When the injection pressure is increased, a large amount of LHCs are formed during the ignition delay period, resulting in high initial heat release rate and short combustion duration. At late diffusing burning stage, high-pressure injection condition produces a smaller amount of gaseous hydrocarbons. When injection pressure is increased, NOx concentration increases during combustion. However higher distillation temperature fuel increases combustion duration which reduces NOx.
- Overall biodiesel emissions are lower than that of diesel fuel except NOx emissions.
- To heat the vegetable oil, external electrical energy has been used to reduce viscosity which leads to better atomization and better mixing.

References

[1] IEA (International Energy Agency). Biofuel for transport: an international perspective, vol. 9. Paris, cedex 15, France: Rue de la Federation; 2004. p. 75739 http://www.iea.org.
[2] Agarwal A. Biofuels application as fuel for IC engines. J Prog Energy Combust Sci 2006;33:233–71.
[3] Demirbas A. Biodiesel fuels from vegetable oils via catalytic and non-catalytic supercritical alcohol transesterifications and other methods: a survey. Energy Convers Manage 2003;44:2093–109.
[4] Griffin Shay E. Diesel fuel from vegetable oils: status and opportunities. Biomass Bioenergy 1993;4:227–42.
[5] Alptekin E, Canakci M. Determination of the density and the viscosities of biodiesel–diesel fuel blend. Renew Energy 2008;33:2623–30.
[6] UNDP (United Nations Development Programme). World Energy Assessment. Energy and the Challenge of Sustainability, New York, 2000.
[7] Giannelos PN, Zannikos F, Stournas S, Lois E, Anastopoulos G. Tobacco seed oil as an alternative diesel fuel: physical and chemical properties. Ind Crop Prod 2002;16:1–9.
[8] Bala BK. Studies on biodiesels from transformation of vegetable oils for diesel engines. Energy Edu Sci Technol 2005;15:1–43.
[9] Erickson DR, Pryde EH, Brekke OL, Mounts TL, Falb RA. Handbook of soy oil processing and utilization. St. Louis, Missouri and Champaign, IL: American Soybean Association and the American Oil Chemists Society; 1980.
[10] Demirbas A. Fuel properties and calculation of higher heating values of vegetable oils. Fuel 1998;77:1117–20.
[11] Demirbas A, Kara H. New options for conversion of vegetable oils to alternative fuels. Energy Sour Part A Recov Util Environ Effects 2006;28:619–26.
[12] Ma F, Hanna MA. Biodiesel production: a review. Bio resource Technol 1999;70:1–15.
[13] Suryawanshi JG, Deshpande NV. Experimental investigation on jatropha oil methyl ester fuelled diesel engine. ASME [ICEF] 2004:866.
[14] Mittelbach M. Diesel fuel derived from vegetable oils, VI, specification and quality control of biodiesel. Bio resource Technol 1996;56:7–11.
[15] Bacho Paul S, Von J, Galante W, Sant Fox, David. Development of a robust injection design for superior deposit resistance. SAE Paper 2005;1:3841.
[16] Ghadge SV, Raheman H. Biodiesel production from mahua [Madhuca indica oil] having high free fatty acids. Biomass Bioenergy 2004;11:2301–4.
[17] Raheman H, Phadatare. Karanja esterified oil an alternative renewable fuel for diesel engines in controlling air pollution. Bio Energy News 2003: 17–23.
[18] Monyem A, Van Gerpen JH. The effect of biodiesel oxidation on engine performance and emissions. Biomass Bioenergy 2001;20:317–25.
[19] Forson FK, Oduro EK, Hammond E. Performance of Jatropha oil in Diesel Engine. Int J Renew Energy 2004;29:1135–45.
[20] Puhan Sukumar, Vedaraman N, Ram Boppana VB, Sankarnarayanan G, Jeychandran K. Mahua oil (Madhuca Indica seed oil) methyl ester as biodiesel-preparation and emission characteristics. Biomass Bioenergy 2005;28: 87–93.
[21] Pramanik K. Property and use of Jatropha oil and diesel fuel in CI engine. Int J Renew Energy 2003;28:239–48.
[22] Nwafor OMI. The effect of elevated fuel inlet temperature on performance of diesel engine running on neat vegetable oil at constant speed conditions. Renew Energy 2003;28:171–81.
[23] Walsh Michael P, Branco GM, Ryan J, Linke RRA, Romano J, Helana M, Marline RB. Clean diesels. SAE Paper 2005;1:2215.
[24] Pundir PB. Engine emissions. New Delhi: Narosa Publishing House Pvt. Ltd; 2007. pp. 224–227.
[25] Bhatt YC, Murthy NS, Datta. Use of non edible oils as fuel for diesel engine. In: Proceedings of Xth National Conference ICEC, vol. 11. 1987. pp. 304–309.
[26] Boehman A. A spray and combustion visualization of a DI engine operated with oxygenated fuel blends. Int J Engine Res 2006;7:503–21.
[27] Gary D, Neely SS, hizuo Yiqun Jeffery H, Stewart AL. New diesel emission control strategy to meet US tier 2 emissions regulations. SAE Paper 2005;1:1091.
[28] Huzayyin AS, Bawady, Rady MA, Dawood. An experimental evaluation of diesel engine performance and emission using blends of jojoba oil and diesel fuel in CI engine. Int J Energ Conserv Manage 2003;45:2112.
[29] Knothe G, Matheaus AC, Ryan TW. Cetane numbers of branched and straight-chain fatty esters determined in an ignition quality tester. Fuel 2003;82: 971–5.
[30] Knothe G, Steidley KR. Kinematic viscosity of biodiesel fuel components and related compound. influence of compound structure and comparison to petrol diesel fuel components. Fuel 2005;84:1059–65.
[31] Graboski MS, McCormick RL. Combustion of fat and vegetable oil derived fuels in diesel engines. Prog Energy Combust Sci 1998;24:125–64.
[32] Yamane K, Ueta A, Shimamoto Y. Influence of physical and chemical properties of biodiesel fuels on injection, combustion and exhaust emission characteristics in a direct injection compression ignition engine. Int J Engine Res 2001;2(No. 4):1–13.
[33] S.V. Lele. Biodiesel in India.J22, sector7, vashi navi Mumbai, 400703, India. Lele@vsnl.com, 2002: website: http://www.svlele.com/Biodiesel in India.html.
[34] Holger H, Thomas C, Robert D, Otfried D. Combined NOx and PM exhaust gas after treatment approaches for HSDI diesel engines. SAE Paper 2004;1:1425.
[35] Kalam MA, Masjuki H. Biodiesel from palm oil – an analysis of its properties and potential. Biomass Bioenergy 2002;23:471–9.
[36] Karaosmanoglu F, Kurt G, Ozaktas T. Long term CI engine test of sunflower oil. Renew Energy 2000;19:219–21.
[37] Okude K, Mori K, Shiino S, Moriya T. PCI combustion or simultaneous reduction of NOx and soot in diesel engine. SAE Paper 2004;1:1002–13.
[38] Kusdiana D, Saka S. Effects of water on biodiesel fuel production by supercritical methanol treatment. Bio-resource Technol 2004;91:289–95.
[39] John B. Heywood internal combustion engines fundamental. Singapore: McGraw-Hill Book Company; 1988.
[40] W.S. Kyle, and C.S. Spencer. Combustion of soybean oil methyl ester in a direct injection diesel engine. SAE Paper 2006-01-930934.
[41] O'Rourke PJ, Amsden A. The tab method for numerical calculation of spray droplet breakup. SAE Paper 1987;872089:1–10.
[42] Reitz RD, Diwakar R. Effect of drop breakup on fuel sprays. SAE Paper 1987;860469:3218–27.
[43] C. Grimaldi and L. Postrioti, Experimental comparison between conventional and biodiesel derived fuel from a common rail injection system. SAE Paper no. 2000-01-1252, pp. 1501–1513, 2000.
[44] Rao PS, Gopalkrishnan KV. Use of non edible oils as diesel engine fuels. Inst Eng [I] J MC 1989:70.
[45] Antony J, Samaga S. Combustion analysis in a compression ignition engine using vegetable oil. In: Bose PK, editor. Proceedings of the Xth national conference on I.C. engines and combustion, vol. 11. New Delhi: Narosa Publishing House; 1987. pp. 234–39.
[46] Verma PCM, Murli Krishna MVS, Prabhakar Reddy C. Investigation on biodiesel (esterified jatropha carcus oil) diesel engines. In: Bose PK, editor. Proceedings of the XVIth national conference on I.C. engines and combustion. New Delhi: Narosa Publishing House; 2000. pp. 159–162A.
[47] Jajoo N, Keoti RS. Evaluation of vegetable oil as supplementary fuels for diesel engines. In: Bose PK, editor. Proceedings of the XVIth national conference on I. C. engines and combustion. New Delhi: Narosa Publishing House; 2000. pp. 151–158.
[48] Gopalkrishnan K, Srinivasa P, Gopalkrishnan KV. Vegetable oil as diesel engine fuel. In: Bose PK, editor. Proceedings of the Xth national conference on I. C. engines and combustion, vol. 11. New Delhi: Narosa Publishing House; 1987. pp. 434–439.
[49] Senthil Kumar M, Ramesh A, Nagalingam B, Gopalakrishnan KV. Performance studies on a CI engine using methyl ester of jatropha oil as fuel. In: Bose PK, editor. Proceedings of the XVIth national conference on I.C. engines and combustion. New Delhi: Narosa Publishing House; 2000. pp. 89–94.
[50] Reddy KV, Babu KR, Ganesan V. Effect of injection pressure on diesel engine performance with vegetable oil: diesel blends. In: Bose PK, editor. Proceedings of the XVIth national conference on I.C. engines and combustion. New Delhi: Narosa Publishing House; 2000. pp. 154–159.
[51] Usta N. Use of tobacco seed oil methyl ester in a Turbocharged indirect injection diesel engine. Biomass Bioenergy 2005;28:77–86.
[52] Vijaya Raju Rao G, Amba Prasad G, Ramamohan P. Esterified Jatropha Oil as a Diesel Engines. In: Bose PK, editor. Proceedings of the XVIth national conference on I.C.engines and combustion. New Delhi: Narosa Publishing House; 2000. pp. 65–75.
[53] Charles Peterson L, Daryl Reece L, Joseph Thompson C, Beck Sidney M, Craig C. Ethyl ester of rapeseed used as a biodiesel fuel – a case study. Biomass Bioenergy 1996;10:331–6.
[54] Cheng CH, Cheung CS, Chan TN, Lee SC, Yao CD, Tsang KS. Comparision of emissions of a direct injection diesel injection diesel engine operating on biodiesel with emulsified and fumigated methanol. Fuel 2008;87:1870–9.
[55] Kalligeros S, Zannikos F, Stournas S, Lois E, Anastopoulos G, Teas Ch, Sakellaropoulos V. An investigation of using biodiesel/marine diesel blends on the performance of a stationary diesel engine. Biomass Bioenergy 2003;24: 141–9.
[56] Y.K. Kidoguchi, Miwa and A. Mohammaddi, A study on thermal decomposition of fuel and NOx formation in diesel combustion using total gas sampling technique. Int J Engine Res 2–3:189–198.
[57] Agarwal D, Agarwal A. Performance and emissions characteristics of Jatropha oil (preheated and blends) in a direct injection compression ignition engine. Appl Therm Eng 2007;27:2314–23.
[58] Agarwal A, Rajamanoharan K. Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine. Appl Energy 2009;86:106–12.

[59] Babcock DG, Konar SK, Mao V, Sidi H. Fast one-phase oil-rich processes for the preparation of vegetable oil methyl esters. Biomass Bioenergy 1996;11-1:43–50.
[60] Pugazhvadivu M, Jeyachandran K. Investigations on the performance and exhaust emissions of a diesel engine using preheated waste frying oil at 135 °C could be used as a fuel. Renew Energy 2005;30:2189–202.
[61] Nazar J, Ramesh A, Nagalingam B. Performance and emission characteristics of a diesel engine using preheated vegetable oil. In: XVIII National conference on ic engines and combustion. 2003. p. 405–10.
[62] Bari S, Lim TH, Yu CW. Effect of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine. Renew Energy 2002;27:339–51.